RATAN-600 – VLA – BTA-6 m ("BIG TRIO") PROJECT: MULTICOLOUR STUDYING OF DISTANT RADIO GALAXIES

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Abstract

Powerful radio galaxies belong to the population of massive stellar systems that can be picked at high redshifts. With measured redshift, morphology and age determination these objects can help greatly in understanding of the way of formation and evolution of giant elliptical galaxies with massive Black Holes in the Early Universe.

We presents some recent results of study of the sample of 105 faint steep spectrum radio sources from RATAN-600 RC catalogue. All the objects has been mapped with the VLA and optical identification have been carried out with the 6 m BTA telescope. Using multicolour CCD photometry in B, V, R_c, I_c bands photometric redshift and age of stellar population are estimated for a subsample of 50 FRII and CSS radio galaxies. RC J0105+0501 is a very probable candidate for radio galaxy at $z \approx 3.5$.

Distribution of objects on colour–colour and magnitude–redshift diagrams shows a rough agreement with expectations of theoretical models of SED evolution for giant elliptical galaxies. On the $[m_R - z_{phot}]$ diagram two populations of faint ($m_R = 22^m - 24^m$) radio galaxies are possibly revealed. The first population at $z \approx 1$ consists of mainly old (a half with age $\geq 5Gyr$) and large ($LAS \sim 20''$) objects, the second one at z = 1.5 − 3.5 includes both younger ($\leq 3Gyr$) and smaller ($LAS \sim 5''$) objects.

There are 12 more faint or still undetected ($m_R \geq 24^m.5$) sources in the sample which may presumably be a very distant radio galaxies ($z > 3.5$) or intermediate redshift old or dusty ones.

1 Introduction

Radio galaxies of FRII type (FRII RGs) belong to the most powerful radio objects of the Universe and at least at low redshifts they are connected with the most massive galaxies with the extreme massive ($\sim 10^9 M_\odot$) and energetic central engines. Evolution of this population and giant Black Hole inside is not well understood yet. Many groups try to check by observations very different scenarios of stellar population evolution existing in literature.

It was realised recently that cm-wavelength 10–50 mJy flux density range is the very interesting: FRII objects dominate here and at the same time they are rather bright yet to be observed optically. Suggested approach optimize the solution of the radio selection of the objects which were born at very high redshifts (HZ). The "Big Trio" project incorporates opportunities of three large telescopes (RATAN-600, VLA and BTA-6 m) to realize a selection of the powerful radio galaxies between extremely deep "pencil beam" very small field surveys (HST, VLA), were fields are smaller than mean distance between HZ FRII RGs, and all sky surveys (NVSS, FIRST, SLOAN), were objects can not be explored deeply ($R > 23$) optically in the most interesting radio flux density range.

2 The sample of RC steep spectrum objects

The "Big Trio" project belongs to the deepest ones in attempts to select the powerful FRII radio galaxies with ultra steep spectra (FRII USS RG) at limiting flux density level below 3C, PKS, B2, GB samples of FRII USS objects.

RATAN-600 RC catalogue of 1145 radio sources in ≈200 sq. degrees strip (at DEC≈ 5°, 40′ wide) with limiting flux density $S_{3.9GHz} \approx 10mJy$ (Parijskij et al., 1991; 1992) was used to select 105 USS objects ($\alpha \geq 0.9$) by cross-identification with a preliminary version (1988), kindly provided by Douglas prior to publication, of $0.365GHz$ Texas (UTRAO) catalogue (Douglas et al., 1996). All selected objects were mapped by VLA to determine precise coordinates, largest angular size (LAS) and radio morphology and optically identified down to $m_R \leq 25^m$ by 6 m Russian telescope (Goss et al., 1992; Kopylov et al., 1995a,b; Fletcher et al., 1996; Parijskij et al., 1996; 1998). Also direct imaging data of 22 objects were obtained at (or near) a subarcsecond seeing with 2.56 m Nordic Optical Telescope at La Palma (Pursimo et al., 1999). In Table 1 ranges and medians of main characteristics of objects of our USS sample are given.

Table 1: Sample of RC USS objects

Parameter	Range	Median
$S_{3.9GHz}$	$15 - 350$ mJy	67 mJy
$\alpha_{3.9}^{0.365}$	$0.9 - 1.5$	1.0
LAS	$\leq 0''.7 - 120''$	$10''$
m_R	$18^m - \geq 25^m$	$22^m.5$

There are 33 compact steep spectrum (CSS) objects in the sample 16 of which has $1'' < LAS < 4''$ and 17 are unresolved or barely resolved ($LAS < 1''$). 65 objects look like FRII and about 20 of them belong presumably to the most distant generation of RGs. 16 objects were classified as quasars by their stellar appearance on CCD images.

3 BVRI-photometry

The technique of multicolour photometry has became in the past few years as the main method in selecting candidates for distant galaxies, and the only approach at very large redshifts. Determination of the age of HZ stellar systems may be the only way of estimation of first

Figure 1: *Contour maps in B, V, R_c, I_c bands of RC J0105+0501. Images with seeing of FWHM=$1''.4$ were obtained in August, 1998 with exposures of 600, 400, 400 and 2×400 s in B, V, R_c and I_c, respectively. Positions of two radio components are shown by pluses. North is up and East is to the left.*

galaxies formation redshift if star formation begins at redshifts larger than z of secondary ionization. Direct observation of protogalaxies predicted by some recent computer simulations are not possible. It was shown (Verkhodanov et al., 1999) that namely BVRI colours are sufficient for accurate estimation of z and age in the redshift range of 0.5–3.5.

We have implemented this approach for 50 FRII and CSS radio galaxies of the RC catalogue that had been observed in B, V, R_c, I_c bands during 1994–1998 with CCD camera on 6 m telescope. Our sample of USS radio galaxies is now the largest one with a four-band optical photometry. The data obtained were used to estimate colour photometric redshifts (z_{phot}) and ages of host galaxies by comparison with two models of evolution of spectral energy distribution (SED) (Fioc and Rocca-Volmerange, 1997; Poggianti, 1997). Few typical cases were checked spectroscopically and reality of the colour z determination was confirmed (Dodonov et al., 1999).

3.1 A high redshift radio galaxy RC J0105+0501

As the best example of high redshift population of our sample we presents $S_{3.9GHz} = 33mJy$ radio galaxy RC J0105+0501 ($m_V = 22^m.5$ complex object at the center of four boxes on Figure 1), which shows the colour properties and the structure characteristic of very distant powerful radio galaxies. In the V band, the galaxy is most extended and is by $1^m.5$ brighter than in the B band, which is interpreted almost unambiguously for the given class of objects as a powerful Lyα line emission and continuum depression in the adjacent region of shorter wavelengths. The negative colour index $V–R_c = -0.3$ and the small index $R_c–I_c$=0.4 are in agreement with this interpretation of the data. The redshift is estimated to be 3.4 ± 0.3. (The first radio galaxy with $z > 3$ was discovered by Lilly (1988), but only about 20 objects of this kind (RG at $z > 3$) have been found so far by joint efforts of different groups. The current "champion" has $z = 5.19$ (Van Breugel et al., 1999).)

It can be seen that in V-band the host galaxy is resolved into two components separated by $1''.7$. (The two brighter neighbouring galaxies, $\approx 4''$ to SW and $\approx 8''$ to SE, are likely to have nothing to do with the radio galaxy since the colour redshift for them is estimated to be about 1.) The SW-component is reliably detected on the B frame and may be an active nucleus of a radio galaxy. The second component may then be either a region of star formation induced by the jet or a gaseous cloud ionized by the radiation from the active nucleus or a combination of both. Other interpretations are also possible. For instance, the active nucleus may be identified with the NE-component or even coincide with the radio component without showing up in optics because of the strong absorption by dust. The necessity of more detailed study of this very fascinating object in the optical, IR and radio ranges for testing different hypotheses on the physics of the processes occurring in this first generation stellar system is evident.

3.2 Colour – Colour distribution

A two-colour distribution of RC-objects so far observed in comparison with PEGASE evolutionary model of giant elliptical galaxy with a formation redshift z_{form}=15 and present day age of 16 Gyr is given on Figure 2. There is a rough agreement between observations and a theoretical model taking into account typical errors in colours of $0^m.2$–$0^m.3$. These are larger for 3 objects most red in $B–R_c$ colour which were observed at the detection limit in B-band. As for 3 objects most blue in $B–R_c$ a strong Lyα line emission in B-band could be suspected (and indeed conformed spectroscopically for one of them (Dodonov et al., 1999)). A plausible explanation for several objects lying inside a dotted contour on Figure 2 may consist in that a noticeable contribution of the active nucleus of galaxy or a mixture of young and old stellar populations is observed. In both cases a shift of $0^m.5 - 1^m.0$ in upper-right direction may bring points to the location of main stellar population of host galaxy. The same effect could explains $R_c–I_c$ colours of group of points below the model curve near $z \sim 1$. Alternatively, a formation redshift, an underlying cosmological model or a stellar content of the SED model could be varied. All these considerations are by no means conclusive until spectroscopic measurement of redshifts will be done. What could be affirmed now is that as a whole the sample of RC FRII USS objects follows in a redshift range of 0.2–3.5 the predictions of PEGASE and, not shown on Figure 2, Poggianti's models of SED evolution of giant elliptical galaxies formed at high redshifts.

4 Magnitude – Redshift diagram

A model of a passively evolving giant elliptical galaxy predicts quite definite magnitude dependence on redshift if star formation in galaxy begins at a rather early time. So a distribution of objects on, for example, a $m_R - z_{phot}$ diagram can be considered as an indirect check of the

Figure 2: *B–$R_c - R_c$–I_c diagram for 50 RGs (objects with $m_R < 20^m$ are shown by open circles and with $m_R > 20^m$ by closed circles) and 10 quasars (crosses). Galaxies with probable strong contribution of AGN light or young stellar population lie inside a dotted contour. Evolutionary track (with redshifts marked) of PEGASE model of giant elliptical galaxy with z_{form}=15 and present day age of 16 Gyr is shown for H_0=50 km/s/Mpc and Ω_0=0.1 cosmology.*

accuracy of photometric redshift estimates for the sample as a whole taking into account that powerful radio sources live as a rule in luminous ($M_R \leq M^* \approx -22^m.5$) elliptical galaxies (if there are no special problems with dust at high redshift, dispersion in z_{sf} and homogenity of the sample).

As can be seen on Figure 3 there is no great contradiction between observed distribution and expected one for Poggianti's model in an "intermediate", $\Omega_0 = 0.45$, cosmological model. The same can be said for PEGASE model (not shown on Figure 3). Unexpected to some extent is rather low mean redshift $< z_{phot} >= 1.6$ for 27 objects with magnitudes of $22^m \leq m_R \leq 24^m$. Formerly we have estimated (Parijskij et al., 1998) that a mean redshift should be of about 2 for such faint objects using 3 types of calibrations (by LAS, α and m_R), based on a large data set from literature on radio galaxies with measured $z \geq 1$. But several effects could help in interpretation of the difference.

Though redshifts, estimated by B, V, R_c, I_c, should be more precise they may has its own systematics. On average we have a fainter radio sources in RC USS sample than in other ones but with lower median α (Table 1). The latter property of the sample my be of greater importance for a selection of HZ objects. Indeed, the calibration by α had given the smallest of all $< z > \approx 1.5$. A more sophisticated interpretation, which seems only speculative until a completion of multicolour observations of remaining objects and spectroscopic redshifts measurements,

Figure 3: $m_R - z_{phot}$ *diagram for 50 RGs. Evolutionary tracks of Poggianti's model of elliptical galaxies of* $M_R = -24^m$ *and* $M_R = -22^m$ *are shown by lines. Inside a box shown by dotted line in upper-right corner 12 very faint or still undetected objects should be located.*

is consisted in that on the $m_R - z_{phot}$ diagram two populations of faint ($m_R = 22^m - 24^m$) radio galaxies are possibly revealed. The first population at $z \approx 1$ consists of old (a half with age $\geq 5Gyr$) and large ($LAS \sim 20''$) objects, the second one at z = 1.5 – 3.5 includes both younger ($\leq 3Gyr$) and smaller ($LAS \sim 5''$) objects. The low z population may becoming to dominate for flux level and typical α of RC USS catalogue, thus providing an explanation of lower mean redshift of the whole sample than expected from calibrations based on objects with higher flux level and steeper spectra.

While all but one of our objects with $m_R < 22^m$ have multicolour data, there are 17 ones with $22^m \leq m_R < 24^m$ and another 12 with $m_R \geq 24^m$ which was not observed in $BVRI$ so far. Most of the latter ones should probably be at $z \geq 1.5$, and some may be a very distant radio galaxies ($z > 3.5$) or intermediate redshift very old or dusty ones.

5 Discussion

Multicolour photometry is of special importance for $z > 2$, where simple (one-band) z_{phot} may give very large errors.

There is increasing interest in the very old distant stellar systems.

Looking at *age* – z relation for our sample of RG, we see well the expected trend for parent galaxies to be younger at higher redshifts, and we believe, that selection effects play a secondary role in this result. We confirm also, that mean epoch of the parent galaxies formation may be in the redshift range 10–20, but in several cases the multicolour ages exceed the SCDM Universe age at the estimated redshift.

First case of that kind we have mentioned in (Parijskij et al, 1996a), another two cases appeared recently (Spinrad et al., 1997; Cowan et al., 1997). These cases were used to estimate the role of the Λ-term (Yoshii et al., 1998; Alcaniz and Lima, 1999). Even more, it was suggested to use *age* – z relation for reconstruction of the physical conditions in the very early Universe (Saini et al., 1999 and Starobinsky, 1999).

It is well known, that errors of colour ages may be small enough for young stellar population, but for old population it is not the case, and, at some redshifts ranges, colours are not sensitive to age at all.

Dust reddening may imitate the old age of the galaxy. But, it can be shown, that separation of these effects may be done, due to the different shape of observable SED.

High importance of the age determination suggests, that all possible ways of the improving ages estimation should be used, and $FeII/MgII$ ratio is one of the suggested for distant objects with emission lines (Yoshii et al., 1998). We hope to select most interesting objects for future studies, including deep spectroscopy.

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References

[1] Alcaniz J.S. & Lima J.A.S. 1999, Astroph. J. Lett., 521, L87 (astro-ph/9902298)

[2] Cowan J.J., McWilliam A., Sneden C. & Burris D.L. 1997, Astroph. J., 480, 246

[3] Dodonov S.N., Parijskij Yu.N., Goss W.M., Kopylov A.I., Soboleva N.S., Temirova A.V., Verkhodanov O.V. & Zhelenkova O.P. 1999, Astronomy Reports, 43, 275 (Astron. Zh., 76, No.5)

[4] Douglas J.N., Bash F.N., Bozyan F.A., Torrence G.W. & Wolfe C. 1996, Astron. J., 111, 1945.

[5] Fioc M. & Rocca-Volmerange B. 1997, Astron. Astroph, 326, 950

[6] Fletcher A., Conner S., Crawford F., Cartwright J., Burke B., Parijskij Yu.N., Soboleva N.S., Kopylov A.I., Temirova A.V., Verkhodanov O.V. & Naugol'naya M.N. 1996, Astronomy Reports 40, 759 (Astron. Zh., 73, 835)

[7] Goss W.M., Parijskij Yu.N., Soboleva N.S., Temirova A.V., Vitkovskij Val.V., Zhelenkova O.P. & Naugol'naya M.N. 1992, Soviet Astronomy, 36, 343 (Astron. Zh., 69, 673)

[8] Kopylov A.I., Goss W.M., Parijskij Y.N., Soboleva N.S., Zhelenkova O.P., Temirova A.V., Vitkovskij Val.V., Naugol'naya M.N., & Verkhodanov O.V. 1995a, Astronomy Reports 39, 383 (Astron. Zh., 72, 437)

[9] Kopylov A.I., Goss W.M., Parijskij Y.N., Soboleva N.S., Zhelenkova O.P., Temirova A.V., Vitkovskij Val.V., Naugol'naya M.N., & Verkhodanov O.V. 1995b, Astronomy Reports 39, 543 (Astron. Zh., 72, 613)

[10] Lilly S.J. 1988, Astroph. J., 333, 161

[11] Parijskij Yu.N., Bursov N.N., Lipovka N.M., Soboleva N.S. & Temirova A.V. 1991, Astron. Astroph. Suppl. Ser., 87, 1

[12] Parijskij Yu.N., Bursov N.N., Lipovka N.M., Soboleva N.S., Temirova A.V. & Chepurnov A.V. 1992, Astron. Astroph. Suppl. Ser., 96, 583

[13] Parijskij Yu.N., Soboleva N.S., Goss W.M., Kopylov A.I., Verkhodanov O.V., Temirova A.V. & Zhelenkova O.P. 1996a, IAU Symp. No. 175, 591

[14] Parijskij Yu.N., Goss W.M., Kopylov A.I., Soboleva N.S., Temirova A.V., Verkhodanov O.V., Zhelenkova O.P., & Naugolnaya M.N. 1996b, Bull. Special Astrophys. Obs., **40**, 5

[15] Parijskij Yu.N., Goss W.M., Kopylov A.I., Soboleva N.S., Temirova A.V., Verkhodanov O.V. & Zhelenkova O.P. 1998, Astronomy Reports, 42, 425 (Astron. Zh., 75, 483)

[16] Poggianti B.M. 1997, Astron. Astroph. Suppl. Ser., 122, 399

[17] Pursimo T., Nilsson K., Teerikorpi P., Kopylov A., Soboleva N., Parijskij Yu., Baryshev Yu., Verkhodanov O., Temirova A., Zhelenkova O., Goss W., Sillanpää A. & Takalo L. O. 1999, Astron. Astroph. Suppl. Ser., 134, 505 (astro-ph/9811265)

[18] Saini T.D., Raychaudhury S., Sahni V. & Starobinsky A.A. 1999, astro-ph/9910231

[19] Spinrad H., Dey A., Stern D., Dunlop J., Peacock J., Jimenez R. & Windhorst R. 1997, Astroph. J., 484, 581

[20] Starobinsky A.A. 1999, this issue

[21] Van Breugel W., De Breuck C., Stanford S.A., Stern D., Röttgering H. & Miley G. 1999, Astroph. J., 518, L61

[22] Verkhodanov O.V., Kopylov A.I., Parijskij Yu.N., Soboleva N.S. & Temirova A.V. 1999, Bull. Special Astrophys. Obs., **48**, 41 (astro-ph/9910559)

[23] Yoshii Y., Tsujimoto T. & Kawara K. 1998, Astroph. J. Lett., 507, L113